Assessment and Evaluation of Soil Ecosystem Services

Nicholas B. Comerford,* Alan J. Franzluebbers, Mary E. Stromberger, Lawrence Morris, Daniel Markewitz, and Rebecca Moore

Soil ecosystem services are diverse, valuable, and underappreciated. They are classified as provisioning, regulating, supporting, and cultural services. This paper is the product of a Soil Science Society of America task force convened to define and value ecosystem services derived from soil for the benefit of scientists, elected officials, and practitioners with the hope that a better understanding of soil ecosystem services will result in informed decisions in the use of soils. Soil provides medicines, building materials, and nutrients. Soil controls nutrient and water cycles. Soil is capable of degrading wastes and detoxifying compounds. Soil is a habitat for diverse microorganisms and fauna, which in turn supports valuable ecosystem services. Soil also supports recreational activities and is part of our cultural heritage evident in legend, religion, song, and art. The value of soil's ecosystem services exceeds that of other parts of an ecosystem, yet the scope and value of soil-derived ecosystem services remains poorly understood. Three of the greatest challenges that remain are to develop (i) a better understanding and documentation of soil biodiversity, (ii) more comprehensive economic valuation of soil services, and (iii) an understanding of how to manage soil to maximize its benefits to humankind.

Nature has endowed the earth with glorious wonders and vast resources that man may use for his own ends. Regardless of our tastes or our way of living, there are none that present more variations to tax our imagination than the soil, and certainly none so important to our ancestors, to ourselves, and to our children.—Charles Kellogg (1941)

Ecosystems are defined by the complex relationships that exist between living resources and their habitats. They are described by their vegetative diversity, by their interactive biotic and abiotic processes and by their climate and soil conditions. When ecosystems are described in the context of the benefits that people obtain from them, these benefits are termed *ecosystem services*. An ecosystem service approach to land management and policy decision making is unique in that it is a people-centric view of nature. It is holistic in that it refers to all the benefits that people receive from the ecosystem, and it is framed in such a way that both market and non-market ecosystem services can be assigned a value—sometimes monetarily, sometimes otherwise. As an introduction to the historic importance of soil to humans, one need only refer to Hillel (1992) and the examples of how the loss of soil fertility resulted in the collapse of ancient civilizations. Here we take a more contemporary view of soil-based ecosystem services.

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Ecosystem services are classified into four categories (Fig. 1). *Provisioning services* are the products obtained from ecosystems

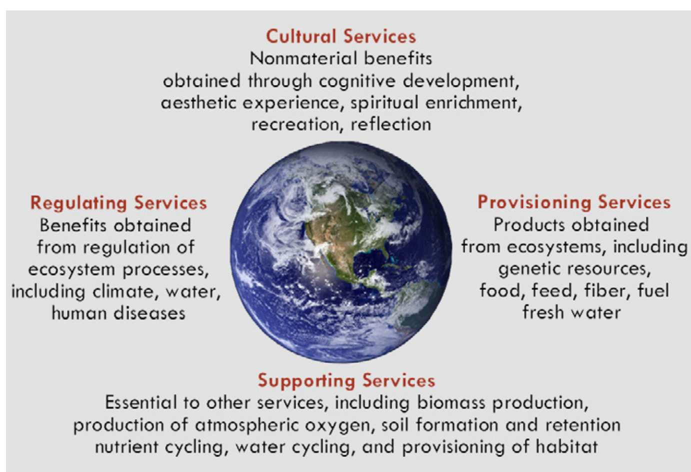

Fig. 1. Categories of ecosystem services provided by nature. Adapted from *Carbon Management*, December 2010, Vol. 1, No. 2, p. 236–251, with permission of Future Science Ltd.

that by and large have a market value. Examples are food, medicines, and fiber. *Regulating services* are advantages gained from the control of ecosystem processes such as pollination and regulation of floods, climate, and disease. *Supporting services* are the necessary foundation for the production of all other ecosystem services. Examples are nutrient cycling and water cycling. *Cultural services* are the nonmaterial benefits that people gain from ecosystems, such as recreation, cultural heritage, aesthetic experience, and spiritual enrichment. The purpose of this paper produced by the Soil Science Society of America task force is to outline ecosystem services derived from soil and provide an overview of their importance, their valuation, and the needs for additional information.

Provisioning Services

Provisioning ecosystem services are products from soil or, where soil material is used, one of the inputs to making products. Soil materials or soil-borne organisms are used in road and building construction, in dishes and china, as fuel, in landscaping, in industries, and as medicines and beauty products (Table 1). Two provisioning services with the most impact on society are those related to construction and medicine. Soil is the real estate we buy and sell and upon which we build our structures. Its physical make-up of gravels, sand, silt, and clay function in a wide range of construction purposes, from paving roads to making bricks. Construction industries are dependent on a number of soil materials, particularly when considering deposits of

Table 1. Provisioning soil ecosystem services.

Use	Sub-use	Soil component	Purpose
Construction	Earth sheltering	Whole soil	Control temperature of a structure
	Landfills	Whole soil	Daily cover
		Clay	Landfill barriers
	Aquarium material	Sand and gravel	Base material and substrate
	Artificial reefs	Sand	Foundation for new reefs
	Beach renovation	Sand	Replace beach lost by erosion
	Road surfacing	Gravel	Road construction
	Walkways and driveways	Gravel	For homes and businesses
	Concrete	Sand and gravel	Making concrete
	Brick manufacturing	Sand	Home construction
	Cores of dams	Clay	Dam construction
Real estate		Whole soil	Commodity
Landscaping	Mulch	Pine straw	Mulch
	Soil replacement	Top soil	Base for grass or gardens
	Potting soil	Top soil	Flowers and gardens, potting mix
		Peat	
	Vermicompost	Earthworms	Garden and soil amendment
Kitchenware	Dishes	Clay	Earthenware, stoneware, porcelain
Fuel		Peat	Heat and cooking
Industrial	Paper coating	Clay	Paper making
	Heat shielding	Clay	Space shuttle
	Insulation	Clay	Temperature control
	Sand blasting	Sand	Cleaning surfaces
	Glass	Silica sand	Glass products
	Paint texture	Sand	Paints
	Foundry molds	Sand	Molds for products
	Toothpaste	Sand	Hygiene
	Filters	Sand/clay	Water and air purification
Medicinal	Antibiotics	Microbes	Ex. Penicillin, streptomycin, etc.
	Sorption	Clay	Adsorbs bacteria to fight diarrhea
Food	Fish bait	Earthworms	Protein and vitamin source
	Human consumption	Earthworms	Protein and vitamin source for some cultures

sand and clay that can occur in shallow to deep subsoils. Soil minerals used in toothpaste, by the electrical industry, and in glass making contrast with the biologically diverse and teeming surface soil that is high in organic matter and is used in landscaping as topsoil and potting media. Landfills and proposed nuclear waste repositories, too, are dependent on soil products. Whole soil material is used daily to cover garbage, while clayey soil is used to make barriers to avoid movement of leachate from these areas.

As many as 22 antibiotics resulted from the work of Dr. Selman Waksman (Waksman, 1958), who won the Noble Prize in Physiology/Medicine for his contributions leading to the discovery of the soil-based antibiotic, streptomycin. New products continue to be discovered, like the soil bacteria *Mycobacterium vaccae*, which has an antidepressant effect on the human brain (Lowry et al., 2007), or the bacteria *Clostridium sporogenes*, which appears to play a role in fighting cancer (Minton, 2003). The potential of new pharmaceuticals coming from soil organisms is enormous considering that only a small portion of the tens of thousands of microbial species per gram of soil has been identified (Hawksworth, 1991)

Regulating and Supporting Services

Regulating ecosystem services control the processes of water flow, energy transfer, nutrient uptake and release, carbon transfer, and chemical processing, as well as services provided by creating and maintaining environments for diverse plant, animal, and microbial communities. A list of these services is provided in Table 2, and selected services are discussed below.

Table 2. Regulating and supporting ecosystem services derived from soil.

Water regulation
Flood mitigation
Water supply and release
Water quality control
Filtering of contaminants
Recycling of wastes
Detoxification of wastes
Erosion control and sediment retention
Soil stability through aggregation
Maintenance of forest floor for physical protection
Cycling processes
Nutrient cycling
Water cycling
Energy cycling
Biodiversity
Biological control of pests and diseases
Habitat to sustain biodiversity that provides redundancy to support processes
Habitat to protect genetic diversity
Greenhouse gas storage/retention
CO_2
N_2O
CH_4

Soil Biodiversity

Soil biodiversity is unique because it is valued both as a product of soil and as a driver of many regulating services. Thus, biodiversity is valued for its own sake as well as for the numerous ecosystem services that its species provide.

There is no better example on our planet of an ecosystem's ability to support species diversity than that of soil. The volume of soil under one square meter of surface soil can support 1000 or more species of invertebrates (Lavelle et al., 2006), while a single gram of soil typically contains thousands of fungal and tens of thousands of bacterial species (Torsvik et al., 2002; Roesch et al., 2007; Buée et al., 2009). This level of diversity is staggering—there are more species in one gram of soil than there are species of mammals on the entire planet.

What makes soil so special in its ability to support life? First, the constantly changing quantity of soil solids, liquids, and gases creates diverse habitats in time and space that vary in size (from micro- to macropores), level of environmental protection (e.g., interior vs. exterior of aggregates), and aeration status (aerobic to anaerobic). A benefit of having different habitat sizes, for example, is that microorganisms residing in aggregate interiors or very small pores can escape predation by larger fauna. This, as well as other factors (such as being able to enter dormancy during periods of environmental stress and exchange genetic material horizontally), has allowed bacteria to experience speciation rates that are greater than extinction rates (Torsvik et al., 2002; Jones and Lennon, 2010). Second, bacteria are incredibly small, ranging from 0.5 to 2 μm in size, and typically occupy less than 1 to 5% of the soil surface area. Many cells are physically isolated from each other, and as a result, species that occupy the same ecological niche can coexist due to absence of competition (Papke and Ward, 2004). Third, soils are spatially and temporally heterogeneous, and thus are able to support a succession of species over space and time. These are just a few explanations, and identifying the mechanisms of how soils support high biodiversity remains a major research topic today.

While we focus on the microscopic in discussion of soil biodiversity, it is important to remember that soil also provides unique habitat for many larger, charismatic, and endangered or threatened fauna. Consider, for example, the gopher tortoise of the southeastern United States. This threatened species makes its burrows only in well-drained, sandy (and, generally infertile) soils of the Coastal Plain (Diemer, 1986; Jones and Dorr, 2004). Shelter provided by gopher tortoise burrows is critical habitat used by more than 60 other vertebrate species (Witz et al., 1991) including the endangered gopher frog (*Rana areolata aesopus*) (Franz, 1986) and indigo snake (*Drymarchon couperi*) (Stevenson et al., 2003), as well as hundreds of invertebrate species.

Why should soil biodiversity be valued? Biodiversity is a genetic resource and represents the potential for biologically mediated soil ecosystem services now and in the future (Table 3). Soil harbors species that can be harvested and utilized for the benefit of humankind. Some of these species are known and are currently being utilized to fix atmospheric N_2 into plant-available N, produce antibiotics to fight infections, provide biological control of crop pests, provide enzymes to bioremediate contaminants in the environment, and so forth. Biological N_2 fixation alone is valued at $44 to 61 billion annually, based on the 2012 U.S. price of urea and global average N_2 fixation rates of 33 to 45 million metric tons of N per year (USDA National Agricultural Statistics Service, 2012; Herridge et al., 2008). Despite their potential economic value, the vast majority of soil organisms (e.g., 95% of soil bacteria) have not yet been described, and therefore, exciting opportunities exist in soil science for exploration and discovery of new species and their potential applications in agriculture and biotechnology.

Ironically, the staggering diversity in soils has often left soil scientists and microbiologists struggling to demonstrate the very importance of that diversity. High diversity also means a high level of functional redundancy, whereby many species contribute in similar ways to a process or ecosystem service. For example, removal of 99% of soil bacterial species failed to reduce rates of respiration, N mineralization, and nitrification in a soil because those activities were maintained by the remaining 1% (Wertz et al., 2006). Nevertheless, recent studies are beginning to show that microbial diversity and the presence of specific "keystone" species are associated with improved plant growth and diversity (van der Heijden et al., 2008) and greater rates of nutrient cycling, including N_2 fixation (Hsu and Buckley, 2009). It is possible that functional redundancy shared among many species increases the likelihood that soils will continue to provide ecosystem services despite disturbance events and land use change (Yin et al., 2000; Girvan et al., 2005), and thus one way biodiversity could be valued is according to its level of functional redundancy.

Can biodiversity be capitalized on for specific ecosystem services? In other words, can soils be managed to promote the growth and activity of specific populations so that specific ecosystem services are provided? In some ways we are doing this already, although not widely and effectively. For example, agricultural and forest soils can and have been managed to promote the activity of plant growth–promoting organisms, including mycorrhizal fungi, N_2 fixing bacteria, and disease suppressing microbes (Berg, 2009; Rooney et al., 2009; Ryan et al., 2009; Singh et al., 2011; Chaparro et al., 2012). This is especially true in organically managed systems, where crop productivity is reliant on soil microbial activity rather than inorganic fertilizers and pesticides. Bioremediation of petroleum spills has high success rates when soils are managed to promote the activity of hydrocarbon-degrading bacteria and fungi through aeration and amendment with fertilizers and solubilizers (Tyagi et al., 2011). There is also growing interest in managing mycorrhizal fungal communities

Table 3. Soil organisms classified according to their regulating ecosystem services.

Major regulating ecosystem services	Specific ecosystem services	Organisms	Specific organism activities
Water infiltration and storage	Water storage	Earthworms, fungi and bacteria	Macropore formation, soil aggregate formation
	Water purification	Nitrate respiring bacteria, fungal and bacterial contaminant degraders, metal oxidizing and reducing bacteria (e.g., sulfate oxidizers, *Geobacter metallireducans*)	Dissimilatory nitrate reduction, co-metabolism and mineralization of organic contaminants, sulfate reduction and subsequent metal precipitation, metal respiration and precipitation
Erosion control	Soil stabilization	Roots, fungi and bacteria	Production of biological glues, physical entanglement by roots and fungal hyphae
Carbon sequestration and greenhouse gas regulation	Litter decomposition and soil organic matter formation	Fauna, fungi and heterotrophic bacteria	Litter fragmentation and decomposition, physical and chemical stabilization of residue carbon
	CH_4 production and consumption	Archaeal methanogens and bacterial methanotrophs	Methane production by methanogens, methane oxidation by methanotrophs
	N_2O and NO production and consumption	Nitrifying and denitrifying bacteria and fungi	Chemoautotrophic nitrification, heterotrophic nitrification, denitrification, and co-denitrification
Supporting crops	Nutrient cycling	Fauna, fungi and bacteria	Nitrogen, phosphorus, and sulfur mineralization, nitrification, bioweathering of P minerals, sulfur oxidation
	Crop growth promotion	Beneficial rhizosphere bacteria and fungi	Production of plant growth hormones, symbioses (mycorrhizal fungi and N_2 fixing bacteria), pathogen control, degradation of stress ethylene (ACC deaminase-positive bacteria)

to facilitate the restoration of native plant communities in degraded soils (Harris, 2009). One could imagine managing soils to promote carbon sequestration by promoting fungal growth and activity, whereby plant residue carbon becomes physically stabilized within aggregate interiors or immobilized within the relatively recalcitrant fungal cell walls (Jastrow et al., 2007). Such purposeful management of soil communities to promote specific ecosystem services is not often used. However, if we are to promote food security and reduce greenhouse gas emissions we may be required to manipulate the communities of soil organisms involved.

Water Regulation: Cycling, Retention, Release, and Purification

Soil plays a key role in water cycling. The portion of precipitation reaching the soil surface that rapidly exits a watershed as storm flow is, in large part, controlled by infiltration and water storage characteristics of soil. The more precipitation that infiltrates into soil, the less that rapidly flows into streams and rivers contributing to flood flows. Urban areas with degraded soil conditions or soil covered by impervious surfaces are more prone to damaging floods than to similar unimpacted areas (Booth et al., 2002; Konrad, 2012). These areas also have lower streamflow during dry periods due to the reduction in the quantity of water that percolates through soil and into subsurface drainage to streams.

In addition to regulating streamflow, soil is a critical reservoir for water retention and release that supports other valued services (e.g., plant growth, soil biodiversity, groundwater recharge). The physical structure of soil is comprised of both micropores and macropores and is uniquely suited to storing water and releasing it at increasing levels of plant demand. In nonirrigated agriculture or natural ecosystems, it is this water capital that sustains ecosystems during intervals between rainfall events. In many areas globally, nonirrigated agriculture depends on soil water capital to sustain crop productivity. In tropical rain forests with extended (3–5 mo) dry seasons large soil volume is critical to provide sufficient water for forest survival due to the enormous green canopy and its high water demand (Nepstad et al., 1994). This soil characteristic extends the period that some water remains available to plants and is an important mechanism limiting mortality during drought.

Soil and the associated plant and microbial communities also clean water by acting as a natural bioreactor. We depend on this capability as a means of treating municipal and industrial wastewater in both large land application systems that serve industry and communities to small on-site systems designed to treat wastewater from individual homes. Soils provide this service through several processes. First, soil physically screens large solids from movement with percolating water. Natural soil profiles appear optimized for such physical screening. In some soil profiles an organic horizon occurs above a coarse-textured surface soil underlain by a finer-textured subsoil horizon. This horizonation provides a sequence where coarse material is filtered at the surface with finer textured materials being filtered at progressively deeper depths, ensuring that the filter does not easily clog. Second, soils selectively retard movement of small colloidal-sized to microscopic particles of both organic and inorganic origin through surface adsorption phenomena. Adsorption phenomena are particularly important in the removal of pathogens and viruses from wastewater. Soil factors affecting pathogen retention and movement are presented in Table 4. Surface adsorption and ion exchange also play an essential role in regulating the chemistry of water absorbed by plants or moving to streams and rivers. An excellent example is sulfate adsorption in subsoils. Lakes and streams in many areas that have been subjected to large amounts of acid precipitation and would be greatly impaired today if it were not for the capacity of some soils to adsorb acids and mitigate deposition impacts. Similarly, the exchange complex regulates and buffers changes in ionic concentrations in solution, playing an important role in both water quality and nutrient supply, which is discussed in the following section.

As mentioned above, soil provides habitat for microorganisms and fauna that are responsible for the decomposition of organic matter and its eventual conversion to CO_2. Within this complex community, organisms exist that are capable of breaking bonds and detoxifying dangerous contaminants. Numerous contaminants have been shown to be detoxified in soil or by microorganisms isolated from soil, including dioxins (Field and Sierra-Alvarez, 2008; Wittich, 1998), solvents such as chlorobenzenes (Gejlsbjerg et al., 2001), polychlorinated biphenyls (Donnelly and Fletcher, 1995; Kubátová et al., 2001), explosives like hexahydro-1,3,5-trinitro-1,3,5 triazine (RDX) (Binks et al., 1995; Crocker et al., 2005), and hydrocarbons from the petroleum industry such as oil and diesel fuel (Das and Chandran, 2011). Mechanisms of detoxification vary, but in most cases they result from microbial production of

Table 4. Factors associated with adsorption of pathogens (viruses or bacteria) to soil.†

Factor	Effect
Water content and flow rate	Slower water movement and lower water contents increase retention.
Reaction (pH)	Lower soil pH increases positive charge and adsorption of viruses.
Texture	Fine textured soils with high clay contents increase retention.
Organic matter concentration	Higher organic matter concentrations increase retention of pathogens.
Soluble organic carbon	Soluble C competes with microbes for adsorption sites and lowers retention.
Cation exchange and base saturation	Increased cation exchange and increased base saturation are associated with increased pathogen retention.
Ionic strength	High ionic strength of soil solution is associated with increased adsorption.

† Based on Atlas and Bartha (1981).

extracellular enzymes that can break specific bonds within contaminant compounds.

Crop and Natural Resource Support and Regulation

Nutrient Cycling

One way that soil supports the growth of crops is by supplying nutrients to plants. It is this nutrient capital, which can be depleted or enhanced, that supports the services we value (Robinson et al., 2009). Of course this supporting service of soil is true not just in agricultural systems, but in all types of ecosystems, including forests, grasslands, and wetlands. Forest harvests, for example, have persisted for millennia, with forest regeneration being largely dependent on soil nutrient capital (Wilde, 1958). Early agricultural systems of slash-and-burn took advantage of this accumulation of soil nutrients by forests to grow crops. After depletion of some components of the soil capital (e.g., nitrogen), soils were abandoned to allow time for soil capital to re-accumulate (Sanchez et al., 1982). Even in the absence of forest regrowth, long-term soil experiments in Rothamsted, England (Powlson et al., 1986) or the Old Rotation in Alabama (Mitchell et al., 1996) have demonstrated an ability of soils to sustain low rates of crop (wheat or cotton) productivity for decades and even centuries.

Soil not only supplies nutrients but also plays a support role in recycling nutrients. This is again true in both natural and managed ecosystems. Nutrient cycles include the conversion of elements in soils from organic to inorganic forms and back. In forests, for example, most plant productivity (i.e., plant leaves, seeds, and fruits) is not consumed by large herbivores but is returned to the soil surface as leaf fall or other litterfall (Cebrian and Lartigue, 2004). These materials are recycled by soil in its support role as the natural bioreactor. This organic matter that includes forms of organic nitrogen (i.e., amino acids) is broken down by the myriad of soil organisms to an elemental form of nitrogen (i.e., ammonium or nitrate) that can be reutilized by a plant or other soil organism. In managed systems organic residues or waste are often added purposefully to soil. Manuring is an age old practice (Lawes et al., 1881) that has benefited human society because of the ability of soils to decompose these organic residues into inorganic elements that are incorporated into the soil capital and once again are made available for plant uptake. Beyond farm yard wastes, this practice has been expanded to the treatment of municipal wastes as a form of tertiary treatment (Morris et al., 2001) and to industrial waste such as residues from pulp and paper mills (Vance, 1996). In each case, soil recycles the "waste" into a useable resource for plant growth. Typically we do not value this recycling function monetarily, but it is critical in supporting the continuing productivity of all ecosystems.

In addition to cycling of organic material, the exchange of inorganic elements with the soil surface provides a valuable buffering mechanism. For example, when soil is fertilized or limed, inorganic exchange processes limit the loss of these materials so that elements are conserved and released over time. This same mechanism can serve to buffer natural processes, such as sulfate adsorption from acid deposition.

Physical Support

In addition to providing nutrients and water, soil supports plant growth by providing a medium to support plant structure. The physical quality of soil is dependent on its ability to provide water, nutrients, and air space but also on the ability of roots to penetrate soil for physical support (Topp et al., 1997). This structural support is most fascinating in the case of tall trees, which may root to a depth of 61 m, have a radial root growth up to 38 m (Stone and Kalisz, 1991) and withstand tremendous forces during wind storms (Fraser, 1962). Of course, we are most aware of this support when the process fails and a tree is blown over during a storm. Gazing at the underside of a wind-thrown tree provides a unique perspective on a soil's supporting role.

Interestingly, it is this kind of soil "failure" that makes many of us consider the critical structural role of soil. Landslides or mudslides are dramatic in their movement of soil. In contrast, the daily structural support that soil provides for our roads and buildings goes largely unnoticed. Structural and civil engineers, however, closely study the soil on which they will build to account for the bearing strength, compressibility, shear strength, and stability (Jumikis, 1967). Soils may support a particular form of road construction in one location (e.g., compaction of clay rich soil), but different soils may require a different approach (e.g., raised gravel bed on organic soils). Throughout the cities and towns of the world soils support our residential, transportation, and industrial activities despite being scalped, physically mixed, deeply compacted, drained, or sealed with impervious surfaces (Richter and Yaalon, 2012). In the absence of supporting soils below our feet, we might be without a roof above our head.

Erosion Control, Carbon Sequestration, and Other Greenhouse Gas Regulation

Soil is a vital component of Earth's climate regulation system, providing key properties and processes controlling energy and water balances, as well as regulating the uptake and emission of a wide array of naturally produced greenhouse gases that keep the climate at a suitable level for human habitation. The ability of plants to fix carbon dioxide (CO_2) and emit oxygen (O_2) is one of the key ecosystem processes that sustain life on Earth. Plant biomass—whether in natural, agricultural, or urban ecosystems—contributes further to gas exchanges not only by drawing down atmospheric CO_2 via photosynthesis, but also by storing some of the fixed carbon in soil as organic matter. Natural ecosystems and conservation-managed agroecosystems are well known for their large storage of soil organic carbon (Eagle et al., 2012), as well as for controlling erosion (Zobeck and Schillinger, 2010).

Soil organic carbon accumulates predominantly in the upper horizons of soils. Without disturbing the soil with tillage, soil organic carbon accumulates as plant residues cover soil and slowly decompose (Schnabel et al., 2001). Protection of the soil surface with plant residues and high soil organic carbon concentration is important for allowing rainfall to infiltrate soil (i.e., lower runoff) and to keep the soil surface from washing away (i.e., lower soil loss). This occurs through development of stable soil structure and biopores that transmit water rapidly from the soil surface to the subsoil. In contrast, unprotected soil from frequent tillage or deforestation lacks such water delivery mechanisms. By helping to control soil erosion and maintain the water cycle in a natural balance, surface-protected soil supports and regulates key ecosystem services. Estimates of soil organic carbon sequestration with conservation management have varied from nearly none in eastern Canada and the northeastern United States to about 1 Mg C ha^{-1} yr^{-1} in western Canada, the northwestern United States, and the southeastern United States (Franzluebbers et al., 2006). Clearly there are regional climate and soil factors that limit how soil carbon changes with a management approach and research efforts are underway to further clarify these factors and their influence on soil.

With the adoption of inorganic fertilizer application in the 20th century, the nutrient supplying capacity of soil organic matter became widely underappreciated. Application of inorganic fertilizer can overcome nutrient deficiencies, even in poorly structured soils with low organic matter. However within a particular soil, the level of organic matter can have a profound influence on the capacity of soil to produce food, feed, fiber, and fuel (Fig. 2). When soils are maintained with high surface-soil organic carbon rather than depleted with accelerated oxidation from repeated tillage operations, productivity can also be enhanced due to non-nutrient attributes of soil organic matter (Franzluebbers and Stuedemann, 2007), such as enhanced aggregation, better water retention characteristics, more diverse microbial communities, and regulation of micronutrient supplies. Accumulation of plant residues and organic carbon in the soil surface is also important for protecting the off-site quality of surface waters in nearby streams and lakes. With increasing surface residue and soil organic C, percentage of rainfall as runoff declines, soil loss declines, and nutrient loss in runoff declines (Fig. 3). In pre-modern times, soil was thought to be at its best when cultivated with implements to release the nutrients stored within organic matter. Lessons from the American frontiers have informed us that preservation of soil organic matter without soil disturbance is a far better goal for preserving the quality of soil for future generations (Lal et al., 2007). The key to sustaining fertility is to

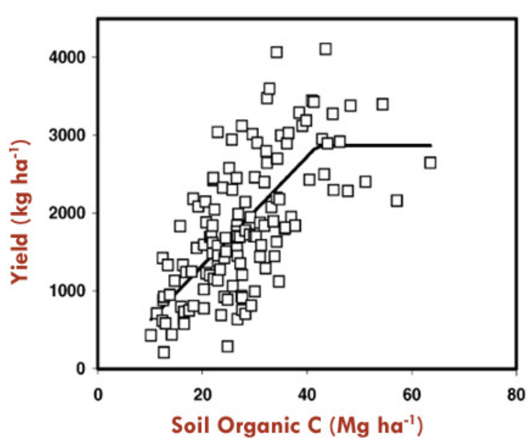

Fig. 2. Wheat grain yield as a function of soil organic carbon content from 134 farmer trials in the Pampas region of Argentina. With degraded soils having soil organic carbon content of 10 Mg C ha^{-1}, 3-yr average wheat grain yield was only 20% of that achieved in high-quality soils with 40 Mg C ha^{-1} (600 vs. 2800 kg ha^{-1}). Soil with 40 Mg C ha^{-1} could be expected to contain 4000 kg ha^{-1} of nitrogen, while a soil with only 10 Mg C ha^{-1} could be expected to contain only 1000 kg ha^{-1} of nitrogen. Assuming 2.5% release of nitrogen each year through mineralization of organic matter, then high-quality soil would be expected to release 100 kg ha^{-1} of nitrogen, while low-quality soil would be expected to release only 25 kg ha^{-1} of nitrogen. Reprinted with permission from Diaz-Zorita et al. (2002).

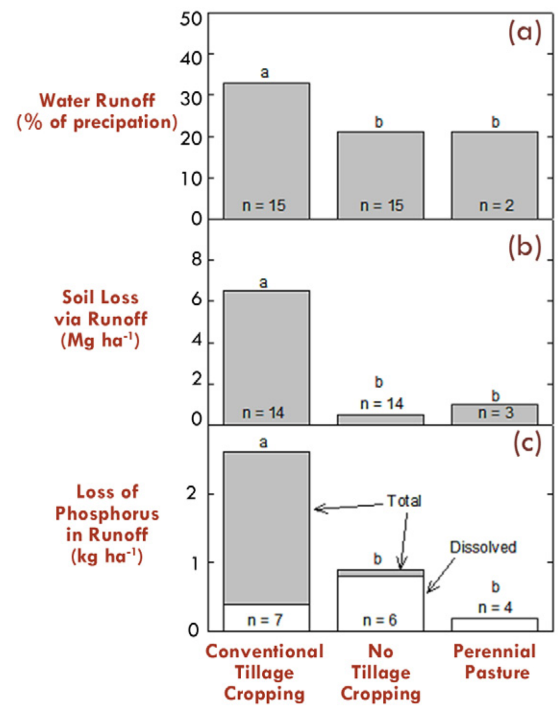

Fig. 3. Summary of how agricultural land use affects (a) water runoff volume, (b) soil loss, and (c) runoff loss of phosphorus in a variety of studies conducted throughout the eastern United States. Data are from multiple sources reported in Franzluebbers (2008). Although soil organic carbon was not reported in all studies, presumed soil organic carbon concentration at the soil surface ranged from lowest in conventional-tillage cropping, intermediate in no-tillage cropping, and highest in perennial pasture. With increasing soil organic carbon following adoption of conservation agricultural management (i.e., no-tillage cropping and perennial pasture), water runoff is reduced, soil erosion is reduced, and nutrient movement into surface water bodies is reduced. With conservation agricultural management, on-site soil quality is enhanced and off-site sedimentation and water quality impairment are greatly reduced. Lower-case letters that are different indicate a statistical difference at the $p < 0.05$ level.

match nutrient requirements of crops with various amendments, whether these come from inorganic or organic sources, such as commercial fertilizers, animal manures, nitrogen-fixing green manures, or various industrial or rurally derived composts. The European-influenced culture of clean, bare soil as a vision of agrarian charm has been rightfully replaced with the modern vision of crop residue–blanketed fields protected from the fierce elements of wind and water, which can be both bane and blessing for the landscape (Franzluebbers, 2010).

Soil is a natural source of emissions for greenhouse gases, including water vapor, CO_2, nitrous oxide (N_2O), and methane (CH_4). Except for N_2O, soil is equally a sink for greenhouse gases. Managing soil in a sustainable manner, therefore, will lead to balanced greenhouse gas cycling, as well as supporting, provisioning, and regulating many other ecosystem services (Greenhouse Gas Working Group, 2010). It is when soils are degraded or managed poorly without regard to sound ecological principles that emission of greenhouse gases from soil becomes a problem. For example, excessively cultivating land beyond its ecological limits leads to soil erosion and loss of soil organic carbon as CO_2, indirect N_2O losses from nitrogen lost to waterways, direct N_2O emissions due to increasing requirements for inorganic nitrogen fertilizer to overcome lost fertility, and emission of CH_4 in waterlogged, poorly structured soil (Liebig et al., 2012).

Cultural and Spiritual Services

These ecosystem services include the non-material benefits that people obtain from their ecosystem and that occur on several levels. In the broadest context, cultural and spiritual ecosystem services are associated with land and landscapes and a "sense-of-place". In a slightly narrower context they include cultural values of specific locations such as battlefields, ceremonial sites, and cemeteries. Soil and land provide images that permeate our written and linguistic heritage and, to a lesser extent, our art. Additionally, cultural ecosystem services include recreation and relaxation.

Land as a sense-of-place has been embodied within the cultural and spiritual beliefs of indigenous peoples throughout the world. In 1854, Chief Seattle of the Suquamish Tribe of what is now the state of Washington spoke about the surrender of native lands to the U.S. government. Much controversy about the origin and exact translation of the speech exists (Abruzzi, 2000), and none of the many versions of the speech is accurate. Nevertheless, the following excerpt from the most well-known translations, done for a film by scriptwriter Ted Perry, is one of the most beautiful statements about the concept of land and place in the English language:

> The great chief in Washington sends word that he wishes to buy our land. He asks much of us … How can you buy or sell the sky, the warmth of the land? The idea is strange to us. If we do not own the freshness of the air and sparkle of the water, how can you buy them? Every part of this earth is sacred to my people. Every shining pine needle, every sandy shore, every mist in the dark woods, every clearing and humming insect is holy in the memory and experience of my people. The sap which courses through the trees carries the memories of the red man. The white man's dead forget the country of their birth when they go to walk among the stars. Our dead never forget this beautiful earth, for it is the mother of the red man. We are part of the earth and it is part of us…

A similar sense-of-place was invoked by President Lincoln (1863) in the Gettysburg Address:

> We have come to dedicate a portion of that field, as a final resting place for those who here gave their lives that that nation might live. It is altogether fitting and proper that we should do this. But, in a larger sense, we cannot dedicate, we cannot consecrate, we cannot hallow this ground. The brave men, living and dead, who struggled here, have consecrated it, far above our poor power to add or detract.

Soil also plays a direct role in our cultural and religious traditions as a physical material. In the Bible (Gen. 3:19) we are reminded of our relationship to soil:

> In the sweat of thy face shalt thou eat bread, till thou return unto the ground; for out of it wast thou taken: for dust thou art, and unto dust shalt thou return.

Indeed, as Hillel (1992) stated, the meaning of Adam in Hebrew is earth or soil. We are from soil and will return to soil. The practice of throwing dirt on the coffin symbolizes this relationship in the Judeo-Christian tradition.

Soil can be considered sacred. A Roman Catholic shrine in New Mexico "El Santuario de Chimayo" in the Archdiocese of Santa Fe is the site of a small pit of holy soil "el pocito" that is believed to have curative powers. Generations of believers have journeyed to Chimayo seeking healing, and each year more than 300,000 people from many different faiths participate in annual pilgrimages to the site. Holy soil from the site is provided by request to the Holy Family of Chimayo.

Imagery of soil and, more generally, earth, permeates our poetry and musical lyrics. The Soil-Net project at Cranfield University, UK, lists more than 50 uses of the word "soil" in poetry, often rhymed with the word "toil" as in Gordon Bottomley's "To Iron-founders and Others" (Bottomley, 1922)

> The generations of the worms
> Know not your loads piled on their soil;
> Their knotted ganglions shall wax firm
> Till your strong flagstones heave and toil.

In 2011, Nathaniel Perry, won the American Poetry Review Honickman Prize for his collection of Poems *Nine Acres*. Titles of the poems were taken from a 1930s handbook on farming such as the poem entitled "Surface Soil Management" (Perry, 2011), which includes the passage:

....we'll grow our food like this, our plans
will look like this—like soil squared
and measured into beds by a man
sweating through his shirt with effort.
In dirt is one life we can choose
to make. I spent the afternoon
breaking what I knew we'd use.

Two examples of the use of soil in lyrics of contemporary music are "Song for My Father" by Brett Anderson (Ball and Anderson, 2007) and "Better Soil" by Amadine (2006). Consider the power of Brett Anderson's lyrics as he remembers his father.

Now my body is sand
And the wind blows through me
Like the soil on your hand
I am compost and leaves
And my life has gone, darling
And now I am free
And my life has gone, darling
Like words made of sand
Like the shivering trees
And my life was a flower
And love was the leaves

The Swedish band Amadine includes the song "Better Soil" on their album *Solace in Sore Hands*. Here, planting seed in better soil is used as a metaphor for placing love where it will grow.

.... So wake up, son
we're moving on
from work and toil
for better soil…

In contrast to the use of soil imagery in song and verse, soil has received less attention in visual arts, often as part of a larger landscape. The earliest representations of landscapes with realistic soil surfaces are included within the works of Konrad Witz in the early 1400s and later in watercolors of Albrecht Dürer (Feller et al., 2010). During this same period, Van der Weyden portrayed realistic soil profiles in his painting *Le Jugement Dernier* (The Last Judgment); however, this and subsequent depictions of soil profiles were largely ancillary to the theme of the images. It is not until the 1900s that images of soil as an object in and of itself began to appear, usually associated with soil science textbooks (Feller et al., 2010), and only recently has soil begun to be perceived as an artistic subject. Guy Paillotin's 1985 oil on canvas *Le Sol* and Van Oort's *Tempete sur Jupiter* (~2000), created from soil materials attached to canvas, are two examples of soil as art. Georgia artist, Mary Charles Howard, used soils collected from a 39-hectare (100-acre) family farm near Sandersville, Georgia to create her painting *Wishbone* (Fig. 4).

Finally, as children we love to play in the dirt. Each pebble is a treasure—each earthworm is a mystery. For those of us who are lucky, the love of digging, planting, and working soil never ends. In 2010, 28% of U.S. households maintained a flower garden, and 26% had a vegetable garden (U.S. Census Bureau, 2012). For more than one-third of these households, recreation was a primary reason for gardening (National Gardening Association, 2009). With its abundance of microbial and faunal life and its ability to spring forth flowers and food, there is no wonder that soil is a joy for so many, in which to work, play, and dream. Indeed, the practice of gardening is recognized as a viable treatment for patients with a wide range of mental and emotional conditions, including transitioning from correctional institutes to freedom (Rice and Remy, 1998) and providing recreation for seniors (Kim and Ohara, 2010). In addition, evidence exists for more rapid recovery from physical trauma and surgery just by viewing gardens, while healing gardens have become an important component of hospital design (Cooper and Barnes, 1999). Therapeutic gardening has emerged as a profession, with its own association (American Horticultural Therapy Association). None of this is possible without healthy soil.

Valuation of Soil Ecosystem Services

As the previous discussion has clearly demonstrated, soil ecosystem services are vital components to all aspects of life. But, while the literature on economic valuation of ecosystem services

Fig. 4. The vibrant and varied colors of soil are displayed in this soil on canvas painting *Wishbone* by Georgia artist Mary Charles Howard. All of the soils used were collected from a 39-hectare (100-acre) family farm near Sandersville, Georgia.

is large and quickly growing, the proportion of this literature that includes quantitative valuation is small (Cornell, 2010). Ecosystem services from soils in particular are relatively unstudied (Dominati et al., 2010). Most of what we know is concentrated on just a few ecosystem services, such as the contribution of soil characteristics to crop production and the value of reducing erosion in watersheds.

Qualitative Valuation

One reason for the lack of quantitative estimates is due to the way economic values are conceptualized and measured. Economic value is a measure of the contribution something makes toward human wellbeing (Brown et al., 2007). The reason to quantify ecosystem service values is that it allows us to better contemplate the tradeoffs common in natural resource management decision-making. When we estimate economic value, we are often interested in all aspects of this tradeoff. The economic value of soil ecosystem services can be separated into both use and non-use components. Use values capture the benefits received by using the resource either directly or indirectly. This might be through provisioning services like providing raw material for construction or pharmaceuticals, or through regulating services like providing flood protection. Non-use value refers to any other benefit or enjoyment gain even without using the resource. Biodiversity and cultural services provided by soil likely have large non-use values. Overall, most of the ecosystem services identified in the previous sections provide significant indirect use and non-use benefits. These are typically the components of value most difficult to quantify.

There are many ways to estimate the economic value of a resource, all of which involve observing tradeoffs people make between that resource and something else with known value. Where there are well-functioning markets, we can use observations of behavior in these markets. But since many soil ecosystem services do not have well-functioning markets, we must rely on non-market valuation methods such as hedonic, travel cost, damage avoidance, and stated preference. Non-market valuation methods (developed during the last 50–80 yr) were designed to estimate the change in benefits provided by the resource due to a change in resource quantity or quality. Rarely is this change limited to soil.

Soil ecosystem services are particularly challenging to value given their supportive role in all ecosystems. The interconnected nature of ecosystems and ecosystem services makes it difficult to determine the contribution on any single component to the overall value of the resource. To avoid double counting of benefits, we can distinguish among supporting, regulating, and provisioning ecosystem services. Ecosystem structure includes the physical and biological components of the ecosystem itself, such as soil characteristics or the quantity of water stored in a soil. Ecosystem processes and functions are the things that link the components of structure. Ecosystem processes support the production of ecosystem goods and services (Brown et al., 2007). Soil itself is part of the ecosystem structure that supports the variety of provisioning, regulating, supporting, and cultural services described above. In valuing an ecosystem service, it is not always possible to separate the value of the service from the underlying components of the ecosystem structure. While most valuation studies estimate the value of changes in the *flow* of ecosystem services, other frameworks discuss the value of soil as natural capital (Robinson, 2009), and consider how ecosystem services augment and deplete that stock, or are dependent on the size and quality of that stock (Dominati et al., 2010). For example, crop production, which can be valued monetarily on a per-bushel basis, is dependent on (i) soil structural benefits such as soil N and plant-available N, (ii) soil process benefits such as N mineralization and denitrification rates, and (iii) soil organic matter turnover and family farm cultural values, all of which are difficult to assign monetary values to, and which are difficult to distinguish to avoid double-counting.

Quantitative Valuation

Existing primary valuation estimates (resulting from original studies of a particular location and/or ecosystem service) are mostly related to agricultural aspects of soil. In such studies the focus has often been on the direct use value of soil or soil nutrients to a farmer, or the off-farm indirect use value and non-use value the surrounding region enjoys when agricultural runoff is reduced. Soil is a benefit when on a farmer's field, but a cost when it becomes sediment in a reservoir. Table 5 lists several original valuation studies and their reported ecosystem service value estimates. These studies used a variety of different methods and estimate values for different products (e.g., $6.2/ton versus $59/ha value of soil erosion). Estimates from each study depended heavily on the characteristics, location, and methodology of the study. Therefore, care must be taken when making inferences from these values. There have been several studies that reviewed, and sometimes aggregated, previous existing studies (Table 6).

When considering the four categories of ecosystem services (i.e., provisioning, regulating, supporting, and cultural), most examples of quantitative value estimates are for supporting services, including nutrient cycling, water cycling, erosion control, and carbon sequestration. Because they are supporting services, it is easier to consider how a change in these services will affect other things we value. How does soil quantity or quality affect the value of cropland or beachfront property? How can forests or grasslands reduce soil erosion and maintain stream benefits? There are also several programs focused on supporting services that provide incentives to landowners who manage their land in a way that protects these services. Federal programs like the Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP) provide payments to farmers for reducing soil and nutrient runoff. In 2010, the average CRP contract for installing and maintaining erosion control structures was $129/hectare ($51/acre). Overall actions of the CRP in 2010

Table 5. Examples of primary soil ecosystem services valuation studies.

Source and description	Example reported value	Valuation method and comments
	Value of soil to agriculture	
Bond et al. (2011) Soil nitrogen and erosion control value to Colorado corn producers	\$1.32 to \$1.50 kg/yr of nitrate leaching \$6.21–\$7.12/ton of soil erosion	Stated choice: Estimates represent the value of irrigation methods that avoid erosion and nitrogen loss
Kassie et al. (2008) Soil conservation of agricultural land in Ethiopia	\$59/ha/yr for erosion control	Production value: Compares the production value of crop land with and without soil conservation technology
Mekuria et al. (2011) Carbon, nitrogen, and phosphorus improvements in Ethiopian grasslands	\$102/ha/yr (net present value over 30 yr)	Market and replacement cost: Uses carbon market prices and local nitrogen and phosphorus fertilizer prices to estimate the net present value of restricting humans and livestock to restore soil quality
Sandhu et al. (2010) Soil formation and mineralization of plant nutrients in agricultural lands in New Zealand	\$0.60–\$11.60/ha/yr for soil formation \$25.00–\$425.50/ha/yr for mineralization	Replacement cost: Soil formation estimates based on the market value of top soil produced by earthworm; mineralization estimates based on market value of nitrogen that would otherwise need to be added
	Off-farm value of reducing erosion	
Colombo et al. (2006) Erosion control in a watershed in Andalusia, Spain	\$14–\$67/person for erosion control project	Stated choice: Estimates mean willingness to pay for a specific erosion control project depending on the characteristics of that project
Hanson and Hellerstein (2007) Erosion control to benefit reservoir management in U.S.	\$0–\$1.38/ton of reduced sediment	Replacement cost: Uses dredging costs to infer the value of reduced reservoir sedimentation
	Other primary studies	
Duffy (2012) Erosion control to benefit rural land values in Iowa	3.4–7.5% decrease in land value due to soil erosion	Hedonic: Relates a change in Corn Suitability Rating to market land values
Jenkins-Smith et al. (2002) Reduced soil contamination (lead, cadmium, zinc) to benefit residential homeowners	\$11,000 loss in home value with contaminant disclosure	Stated preference: Compares willingness to pay for housing near a former industrial site with and without disclosure of potential toxic soil contamination

Table 6. A review of valuation studies that include soil ecosystem services.

Source	Ecosystem services included
Costanza et al. (1997) Broad-scale estimate of value of global ecosystem services using benefit transfer	Erosion control: \$576/ha/yr Soil formation: \$53/ha/yr Other services: Depend on soil but review does not explicitly value the role of soil in these services. These are averaged values from several original studies that vary in terms of ecological and social characteristics and methodology. These estimates suggest an order of magnitude, but care should be taken when making inference to a specific application.
Everard et al. (2010) Review of the value of sand dunes	Includes a qualitative scoring ranking the relative importance of sand dunes for providing multiple provisioning, regulating, cultural, and supporting services. No monetary valuation included.
Gorlach et al. (2004) Comprehensive review of soil ecosystem services in Europe	Erosion: \$21–\$208 ha/yr Contamination: \$0.12–\$0.37/ha/yr for Europe Salinization: \$288–\$588/ha/yr for 3 countries These are upper and lower bounds based on case studies and several previous studies. The original studies vary in terms of ecological and social characteristics and methodology, so these estimates indicate order of magnitude values.
Kreiger (2001) Review of estimates of forest ecosystem service values including watershed services, recreation, and cultural values	Soil stabilization: Considers role of forests in preventing sedimentation in watersheds. Reports estimated avoided costs from three studies: \$1.94/ton of sediment avoided in Tennessee \$5.5 million/yr in Oregon \$90,000 in Arizona Other services: Depend on soil but review does not explicitly value the role of soil in these services.
Pimental et al. (1997) Broad-scale estimate of biodiversity value in USA, estimates the provisioning service provided by soil biota	Soil formation: Earthworms provide topsoil valued at \$5 billion/yr. Other services: Soil plays a role but is not explicitly evaluated.

were estimated to reduce erosion by 200 million metric tons nationwide as well as reduce nitrogen loss by 680 kilograms (607 pounds) and phosphorous by 137 kilograms per hectare (122 pounds per acre) (Conservation Reserve Program, 2010). Similar landowner incentive programs are run and being developed by state and regional level institutions (Mercer et al., 2010).

Provisioning services are easiest to value when there are well-functioning markets for the good. This is the case for many of the construction and pharmaceuticals goods provided by soil. However, in regions where subsistence harvesting of soil biota for food is an important contribution to diets (e.g., mushrooms), there are no market data from which to estimate value. For regulating services (e.g., biodiversity, flood control, and water filtration), soils are typically considered part of the ecosystem structure and are not directly valued. In terms of valuation, it would be helpful to better understand the linkages between soil quantity and quality and these regulating services. Holding other ecosystem characteristics constant, how does an increase in soil quality—aggregate stability—affect flood frequency and intensity? A similar question applies to valuing the cultural services of soils. Studies have estimated the value of cultural services from forests, wetlands, parks, historic sites, art, and more, yet soil is inseparable from theses ecosystems and rarely valued independently.

Conclusions

Ecosystem services provided by soil are diverse, valuable, and often underappreciated or aggregated into larger system evaluations. Soil directly provides medicines, building materials, and nutrients. Soil controls nutrient and water cycles. Soil is capable of degrading wastes and detoxifying compounds. Soil is a habitat for diverse microorganisms and fauna, which in turn provide many valuable ecosystem services. Soil supports recreational activities and is a part of our cultural heritage. The value of soil's ecosystem services quite likely exceeds that of other parts of an ecosystem, yet the full scope and value of soil-derived ecosystem services remains poorly understood. Three of the greatest challenges remaining to be uncovered are (i) developing a better understanding and documentation of soil biodiversity, (ii) providing more comprehensive economic valuations of soil ecosystem services, and (iii) understanding how to manage soil to maximize its wealth of ecosystem services for the betterment of humankind. Soil science will have matured when we can comprehend the scope of ecosystem services derived from soil, learn how to manage soil to solve society's problems, and be certain that our society understands soil's overall value.

> *While the farmer holds the title to the land, actually it belongs to all the people because civilization itself rests on the soil.*—Thomas Jefferson

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